MULTIMEGAMPERE OPERATION OF PLASMA COMPRESSION
OPENING SWITCHES IN PLANAR GEOMETRY*

J. H. Goforth, D. J. Erickson, A. H. Williams and A. E. Greene

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Abstract

Experiments are described in which a plasma compression opening switch is used in planar geometry to sharpen the output pulse of an explosive-driven magnetic flux compression generator. Included are data from tests where peak opening switch currents range from 5.7 to 9.3 MA. The switch is used to transfer current to a static low-inductance load (~10 nH) with an efficiency of 50% or better and a risetime as low as 0.45 μs. Results related to current transfer are interpreted within a simple analytical model.

Introduction

Pulse sharpening with a plasma compression opening switch technique was first reported by Pavlovskii et al.[1] The opening mechanism in their switch was an increase in plasma resistance caused by the explosive compression of a cylindrical plasma cavity. The power source in the Pavlovskii experiment was an explosive-driven magnetic flux compression generator. We have adapted the plasma compression technique to planar geometry for use with plate-type explosive generators.[2] In work reported previously,[3-5] small scale tests were performed at moderate currents to establish parameters for the technique. These smaller devices employed high quality, inexpensive plane-wave lens detonation systems. We report here the results of experiments with switches that are increased in size for currents in the 5-10 MA range. Used with plate generators, these switches now provide a practical source for current pulses with risetimes of a microsecond or less. The results presented here are from experiments that characterize the opening switch in circuits containing static, low inductance loads. Other papers in this conference report on the use of the switch to drive a dynamic Z-pinch load.

Pulsed Power System

The circuit for the system is shown in Fig. 1. The components are an explosive generator denoted by a time-dependent inductance L_1, an opening switch represented by L_2 and a variable resistance R_2, a closing switch S and a load L_3. Transmission line inductances are lumped into the component parameters. The generators used in our experiments are described by Caird et al.[2] Typical generator characteristics are initial inductance of 250-300 nH, peak source impedance of 30-40 mΩ, and generator (flux) compression time of 14-15 μs. Into very low impedance loads (a few nH and a few mΩ), the plate generators used here are capable of producing currents as high as 15 MA.

The planar opening switch is shown in Figs. 2 and 3. The top plate of the parallel plate combination is shown in Fig. 2. The generator is attached to the upper and lower plates of this combination at position 1. The load assemblies, isolated by closing switches, are attached at positions 2 or 3. A side view cutaway of the switch is depicted in Fig. 3. A capacitor bank (not indicated in Fig. 1) is used to drive current through the generator and opening switch to establish magnetic flux in the generator and to create conducting plasma in the switch channels. The plasmas are initiated from thin films of aluminum that

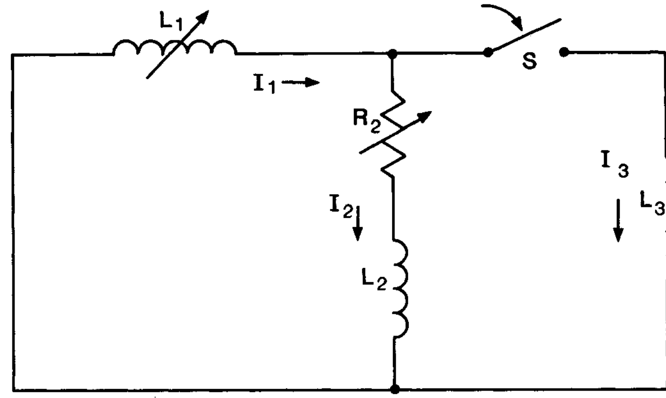

Fig. 1. Circuit for opening switch tests.

have been vapor deposited on the Teflon insulators. Current flows radially inward in the upper channel of Fig. 3, and outward in the lower channel. Plasma compression is obtained from the breakout of planar detonation fronts from the explosive disks. The high quality fronts are obtained from explosive lenses (not shown), which are placed on the PBX 9501 compression charges.

The closing switches were arranged in a variety of multichannel line configurations. In all cases they used sheets of polyethylene to separate switch electrodes. The polyethylene sheets were punctured in a number of places by the action of small explosive charges. The sensitivity of these devices to the voltage across the switch dielectric requires in situ testing to determine precise switch closing time under experimental conditions. We have used the switches to hold off and then close at voltages from 20 to 70 kV.

The loads for these experiments were single-turn coil blocks designed for a specific fixed inductance. Initially, we connected a single 15-nH load at position 2 of Fig. 2. In order to decrease the effective load inductance in subsequent experiments, we used parallel loads at positions 3. In the latter configuration the load inductances were reduced to 6-8 nH.

The desired sequence in operating the pulsed power system begins with loading the initial flux into the circuit and generating the conducting plasma in the switch cavities. The capacitor bank discharge for this process requires about 40 μs. The explosive generator is then actuated, first trapping the initial flux in the generator volume and then compressing it to amplify current in the circuit. At an appropriate time, the plasmas in the opening switch are compressed, giving rise to a fast increase in the plasma resistance. As the voltage rises across the opening switch, the closing switch is actuated to allow current to flow in the load.

In each of our experiments, Rogowsky coils were used to measure dI/dt in the generator, opening switch and load branches. These signals were passively integrated to obtain the branch currents. Voltage across the opening switch was measured by monitoring the current through a $CuSO_4$ shunt resistor with a Pearson self-integrating current monitor. These diagnostics

*Work supported by the US Department of Energy.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 1985**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Multimegampere Operation Of Plasma Compression Opening Switches In Planar Geometry**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Los Alamos National Laboratory Los Alamos, New Mexico 87545**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT
Experiments are described in which a plasma compression opening switch is used in planar geometry to sharpen the output pulse of an explosive-driven magnetic flux compression generator. Included are data from tests where peak opening switch currents range from 5.7 to 9.3 MA. The switch is used to transfer current to a static low-inductance load (-10 nH) with an efficiency of 50% or better and a risetime as low as 0.45 ~s. Results related to current transfer are interpreted within a simple analytical model.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

were sufficient to determine the time dependence of the opening switch resistance as well as the switch power and dissipated energy.

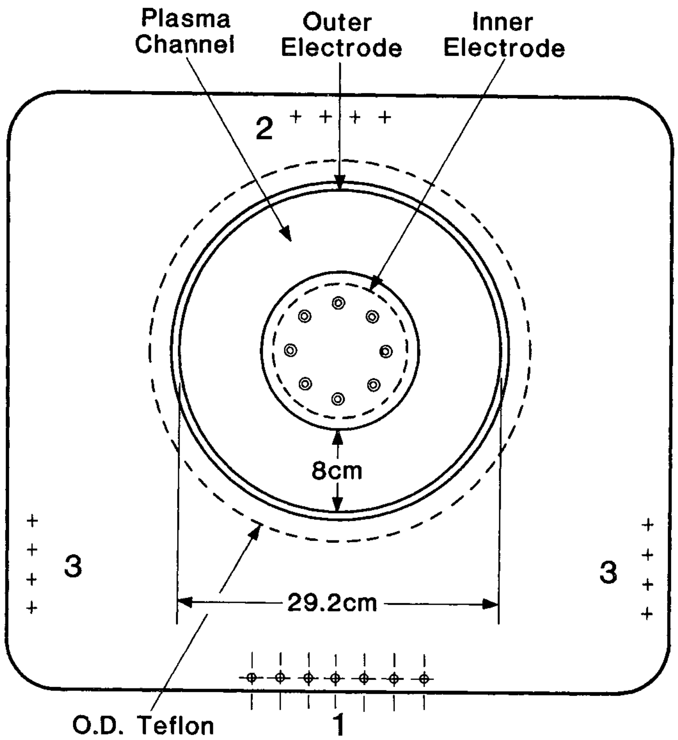

Fig. 2. Top view of planar plasma compression switch. Current flows radially between inner and outer electrodes. Generator attaches at 1 and loads at either 2 or 3.

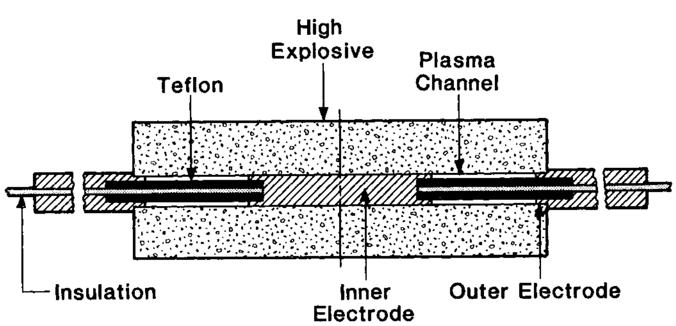

Fig. 3. Side view cutaway of planar plasma compression switch. There are identical geometries on both sides of the device although components are only labelled on one side. Plasma cavities are 0.3 cm thick, and the plasma is initiated from 0.5 μm thick aluminum films deposited on the annular Teflon surfaces. The high explosive is 2.5 cm thick and 30.5 cm in diameter.

Results

The performance of our pulse power system is illustrated in Fig. 4, which includes the most important waveforms from one of our tests. To reveal the details of interest, we show only a 3-μs interval late in the generator compression time. The currents shown are those measured in each branch of the circuit of Fig. 1. At times prior to switching in the load, $I_1 = I_2$. After that time $I_1 = I_2 + I_3$. The measured voltage across the opening switch and dI_2/dt through it are also shown. These two curves and I_2 are used to determine the opening switch resistance from the relationship $R_2 = [V - L_2(dI_2/dt)]/I_2$, assuming $L_2 = 7$ nH as measured in our tests. The resistance curve shown in Fig. 4 is, however, not completely typical of our experiments. In many of the experiments, the decrease in resistance seen in Fig. 4 (beginning at ~14.3 μs) is followed by a further increase some 0.2-0.3 μs later.

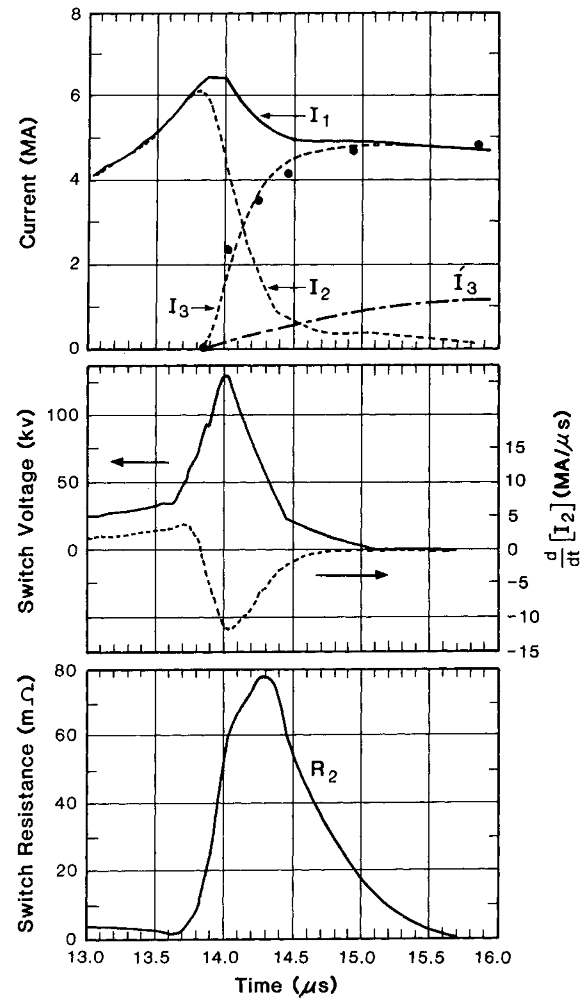

Fig. 4. Performance data from an opening switch test. I_1 and I_3 are also shown as experiment D in Figs. 5 and 6.

The experimental parameter that presently correlates most closely with the post-peak resistance behavior is the I^2R power developed in the opening switch. The peak power in the experiment of Fig. 4 is 1 TW. In a similar test where the power level reached only 0.8 TW, the resistance curve tracked that shown in Fig. 4 until its decrease to 50 mΩ. It then recovered, increased to more than 80 mΩ by 14.8 μs, and continued to increase until the diagnostics were destroyed a short time later. A useful resistance spike has been generated in another experiment with a peak power of ~1.4 TW. But in a test where a peak of 1.7 TW occurred, the initial resistance spike failed to exceed 30 mΩ, and dropped to 10 mΩ after the initial spike. While further work is required to

quantify this relationship, it presently appears to be a useful indicator of switch limitations.

Our system has been found to operate well over a limited parameter range. To demonstrate its capability within this range, we compare generator currents (I_1) in Fig. 5 and load currents (I_3) in Fig. 6 from four tests. Experiment D is that shown in the data of Fig. 4. As discussed in the previous section, we performed experiments with different load inductances. We also varied the timing of the opening/closing switching sequence with respect to generator compression and varied the relative timing between the opening and closing switches. Table I summarizes parameters which characterize the load pulses.

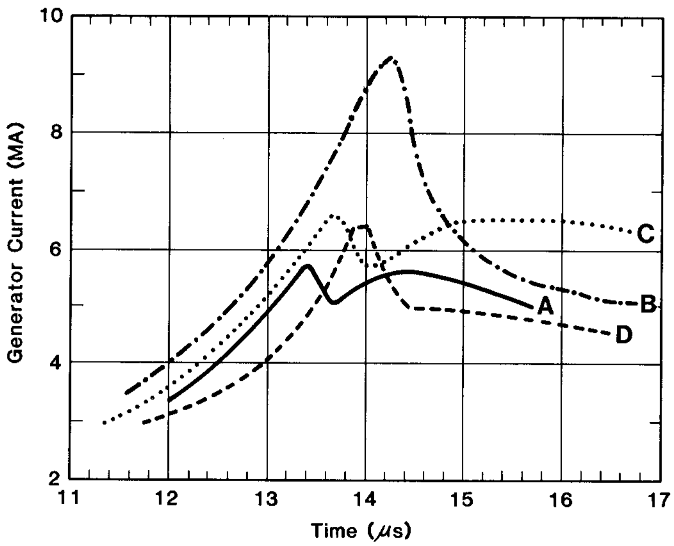

Fig. 5. Final few microseconds of generator current pulse for four experiments. Generator flux compression begins at zero on this time scale.

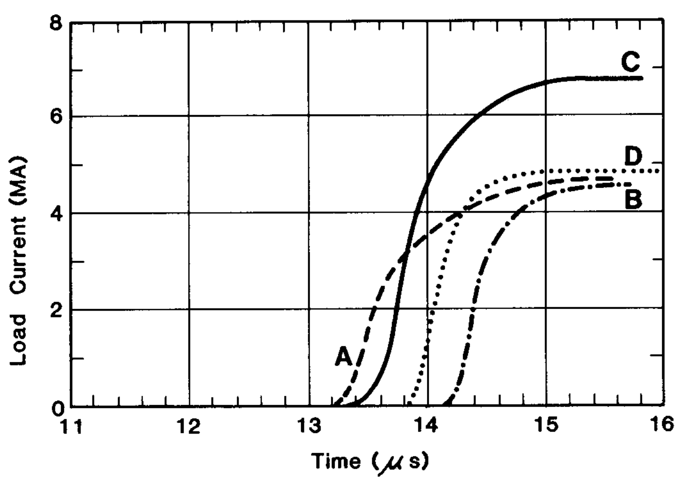

Fig. 6. Load pulses for tests shown in Fig. 5.

Table I. Load Pulse Parameters

Experiment	I_3(max)	Risetime (e-fold)	Risetime (10-90%)	L_3
A	4.7 MA	0.45 μs	1.10 μs	15.0 nH
B	4.6	0.35	0.54	15.0
C	6.7	0.45	0.90	6.5
D	4.8	0.30	0.45	8.0

In examining the generator currents in Fig. 5, we first point out that they peak at different times due to actuation of the opening switches at different times. In the absence of switching, the currents would have achieved roughly the same peak value at the end of the generator runs, ~15 μs for experiments A-C and ~14 μs for experiment D (due to geometry adjustments in the generator). We also note that the voltage produced by the opening switch overwhelms the generator/source output for a short time. If this occurs near the end of the generator compression pulse, generator peak current is determined by the onset of the opening switch action. This is the case for each of the curves shown, although A and C show some recovery due to further flux compression. The other variation caused by changing the timing of the switching sequence is in the circuit current ($I_1 = I_2$) prior to switching.

The differences in the initial rate of rise of the load currents in Fig. 6 illustrate the effect of altering the relative timing between the opening and closing switches. Curve C, for instance, was generated by closing the load circuit switch ~150 ns before the onset of the resistance rise in the opening switch, while the more abruptly rising curve D was obtained by closing the load switch after the voltage had begun to rise across the opening switch. A reasonably accurate measure of this difference can be made by comparing the time of generator current peak in Fig. 5 to the time of initial load current. Apart from those features due to variations in relative opening/closing switch times, the load current pulses are determined by the circuit parameters and the timing of the transfer process with respect to the generator pulse.

Simple Model

It is instructive to examine our results in terms of a simple analytical model. At some arbitrary time t_o, the circuit in Fig. 1 is assumed to have a storage inductor L_1 with fixed inductance, a fixed resistance R_2, and a current I_o which flows through L_1 and R_2. As switch S closes instantaneously, current is transferred to L_3 according to

$$I_3 = \frac{L_1}{L_1 + L_3} I_o[1 - e^{-(t-t_o)/\tau}] \text{ , where}$$

$$\tau = \frac{L_1L_2 + L_1L_3 + L_2L_3}{R(L_1 + L_3)} .$$

Within the assumptions of the model, the peak current transferred is a function of the store L_1 and the load L_3. Further, the maximum load current is approached with a time constant τ that is a function of the circuit inductances and the opening switch resistance.

To apply the model to our experiments, we set L_1 equal to the inductance of the generator at closing switch time, I_o equal to the current ($I_1 = I_2$) just prior to closing switch time, and R_2 equal to some resistance in the opening switch. To a first approximation, we ignore the time dependence of the generator during the load pulse and make the following observations. Since L_1 decreases in time as I_o increases, we have available a smaller fraction of a larger current when we actuate the switching sequence later in the generator run. The transfer rate, however, increases as the generator inductance decreases. As a result, peak current, transfer efficiency and transfer time are dependent on the choice of switch time.

Such behavior is evident in our data. Experiments A and B in Figs. 5 and 6 show the effect of switching at different times in the generator run. By normalizing A to the same generator current profile as B, the load current pulse A should have reached a peak of 5.5 MA with an e-folding time of 0.45 μs. Although the current in the opening switch has exceeded 9 MA in experiment B at switch time, only a 4.6 MA peak load current is achieved, but with a faster e-folding time of 0.35 μs. Comparing curves A and C reveals the expected effect of reducing the load inductance for better transfer efficiency at comparable risetimes. Finally, curve D is a reasonably optimized experiment in which a good ratio of system inductance is coupled with relative opening/closing times adjusted for the fastest initial current rise. An inductance of ~20 nH is estimated for L_1 at switch time in this experiment, and 75% of peak current is transferred to the load with an e-folding time of 0.30 μs.

In each of these experiments, some flux compression does indeed occur during the load pulse. This has the effect of increasing peak load current above that predicted by the term $I_0L_1/(L_1 + L_3)$. Such an effect is greater in experiments where the switching time is earlier in the generator compression run. However, in none of the experiments discussed here is the inductance $L_1 + L_3$ reduced by more than 30% during the load pulse. With no losses, a 30% reduction in $L_1 + L_3$ would provide for a peak current 1.3 times the value predicted in our simple model. The effect is reduced when losses are included.

Finally, we compare the results of a fit of our model to the current transfer data of experiment D. This experiment is selected for comparison since very little flux compression remained after switch time. We should therefore see the least deviation from our model. A value of 20 nH for the generator inductance is obtained from an appropriate generator model and experimental timing. Values for L_2 and L_3 (7 and 8 nH) were measured prior to the experiment. The load pulse I_3 has been calculated as a function of time assuming values for I_0 from the data in Fig. 4. A value of R_2 = 40 mΩ was selected for a best fit. Representative points from the calculation overlay the measured waveform for I_3 in Fig. 4. Since the switch resistance increases on a time scale similar to that of the load pulse, a square wave resistance to simulate the actual data has a substantially smaller value than the peak resistance observed in the data. For purposes of evaluating the usefulness of our switch for a given load, however, it appears that using a square wave resistance of 40-50 mΩ gives a reasonable simulation for pulse lengths ≥ 0.3 μs. We also show in Fig. 4 the current I'_3 that would have been transferred in experiment D if the opening switch had remained at its initial resistance of ~1.5 mΩ. Comparison of this latter curve with the measured curve shows the dramatic pulse compression achieved with the switching system.

Conclusions

Explosive-driven plasma compression switches can be used in planar geometry to transfer current from inductive stores at currents up to 10 MA. A simple model can be used to determine the peak current and risetime for a pulse transferred to a static inductive load. Although the use of the model to describe explosive-generator-powered experiments requires additional consideration of the time dependence of the generator inductance, actual flux compression details can be neglected in many circumstances. As long as power levels do not significantly exceed 1.5 TW, the switch can be treated approximately as a 40-50 mΩ square wave resistance in the simple model. This result holds for pulses that e-fold in times ≥ 0.3 μs.

References

[1] A. I. Pavlovskii, V. A. Vasyukov and A. S. Russkov, "Magnetoimplosive Generators for Rapid-Risetime Megampere Pulses," Sov. Tec. Phys. Lett. 3, pp. 320, 1977.

[2] R. S. Caird, D. J. Erickson, C. M. Fowler, B. L. Freeman and J. H. Goforth, "A Circuit Model for the Explosive-Driven Plate Generator," in Ultrahigh Magnetic Fields-Physics, Techniques and Applications, V. M. Titov and G. A. Shvetsov, eds. Moscow: Nauka, 1984, pp. 246-253.

[3] J. H. Goforth, R. S. Caird, R. F. Benjamin, D. J. Erickson, C. M. Fowler and B. L. Freeman, "Fast Explosive-Driven Opening Switches Carrying High Linear Current Densities," ibid., pp. 338-394.

[4] A. E. Greene, J. H. Brownell, T. A. Oliphant, G. H. Nickel and D. L. Weiss, "Computational Simulations of Explosive-Driven Plasma-Quench Opening Switches," in Proceedings of the 4th IEEE Pulsed Power Conference, T. H. Martin and M. F. Rose, eds. Lubbock: Texas Tech Press, 1983, pp. 790-793.

[5] J. H. Goforth and R. S. Caird, "Experimental Investigation of Explosive-Driven Plasma Compression Opening Switches," ibid., pp. 786-789.